

# **National Compact Stellarator Program**

**J. F. Lyon, ORNL  
representing the  
US Compact Stellarator Community**

**DOE Budget Planning Meeting  
Gaithersburg, MD                      March 15, 2005**



# Main Topics

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- **US compact stellarator program logic**
- **Experimental facilities and programs**
- **Contributions to FESAC's priority questions**
- **Budgets and near-term objectives**

# Programmatic Approach

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- **US compact stellarator program uniquely integrates three features in experiments**
  - **compactness (low aspect ratio)**
  - **quasi-symmetry (low ripple and flow damping)**
  - **good flux surfaces (finite, low plasma current)**
- **Goal -- steady-state disruption-immune toroidal plasmas with performance comparable to, or better than, that of tokamaks**
- **Possible because recent advances in 3-D theory and computation allow design of optimized configurations**
- **Motivation -- excellent results from larger aspect ratio stellarators without benefits of quasi-symmetry**

# Compact Stellarators Offer Solutions to Steady-State Burning-Plasma Challenges

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- **Steady-state compatible, quiescent high-beta plasmas already demonstrated without disruptions.**
  - provides alternate solution to high-bootstrap-fraction Advanced Tokamak
  - allows ITER to lead to the next step (DEMO), even if disruption-mitigated, steady-state, high-bootstrap-current operation is not fully attained
- **Soft operating limits, not disruptive. Allows higher density operation**
  - allows low temperature edge, should ease divertor design.
  - decreases drive for fast ion instabilities
  - provides alternative solutions for ITER challenges
- **Orbit physics and turbulent transport physics of quasi-symmetric stellarators is directly connected to tokamak understanding. Thus, contributes to, and benefits from, ITER understanding.**

# Energy Vision: a More Attractive Reactor

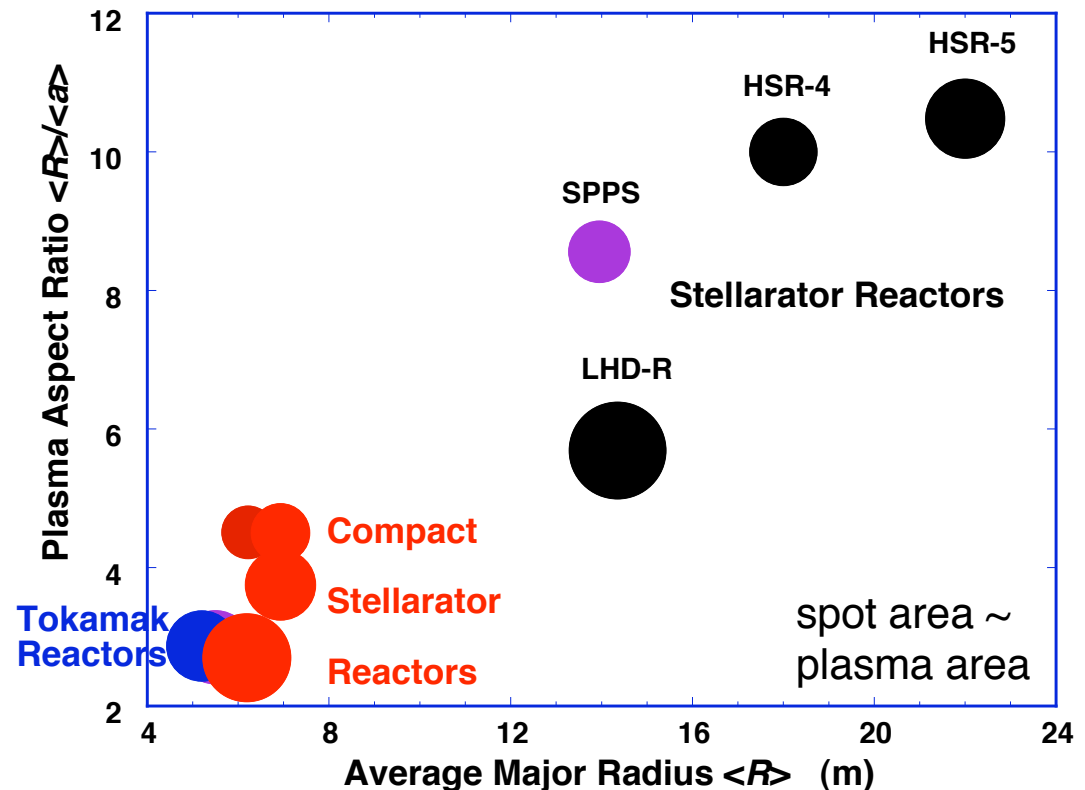
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- A steady-state toroidal reactor with
  - No disruptions
  - No near-plasma conducting structures or active feedback control of instabilities
  - No current drive ( $\Rightarrow$  minimal recirculating power)
  - High power density ( $\sim 3 \text{ MW/m}^2$ )
- Likely configuration features (based on present knowledge)
  - Rotational transform from a combination of bootstrap and externally-generated (how much of each?)
  - 3-D plasma shaping to stabilize limiting instabilities (how strong?)
  - Quasi-symmetric to reduce helical ripple transport, alpha-particle losses, flow damping (how low must ripple be?)
  - Power and particle exhaust via a divertor (what topology?)
  - $R/a \sim 4$  (how low?) and  $\epsilon > 4\%$  (how high?)
- Design involves tradeoffs -- need experimental data to quantify mix and assess attractiveness

# Reactor Concept Improvement

- **Stellarator advantages**
  - inherent steady-state capability with no disruptions
  - fully ignited operation with no power input to the plasma
  - no need for rotation drive or feedback control of instabilities

- **Compact stellarator reactors can be comparable to tokamaks in compactness**



# The US Compact Stellarator Program

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The components of the integrated national compact stellarator (CS) program

- HSX and CTH (existing university experiments)
- NCSX (under construction)
- QPS (R&D and prototyping phase)
- Theory and modeling
- International collaborations, ARIES reactor study

address important US program issues using CS's unique features: quasi-symmetry and configuration flexibility

- to advance toroidal confinement understanding
  - MHD stability; disruption immunity without instability feedback
  - reduced neoclassical and anomalous transport
  - natural divertor for particle & power handling
- for concept improvement
  - quiescent steady state, without current or rotation drive
  - factor 2-4 lower aspect ratio than conventional stellarators
  - smaller reactor embodiment

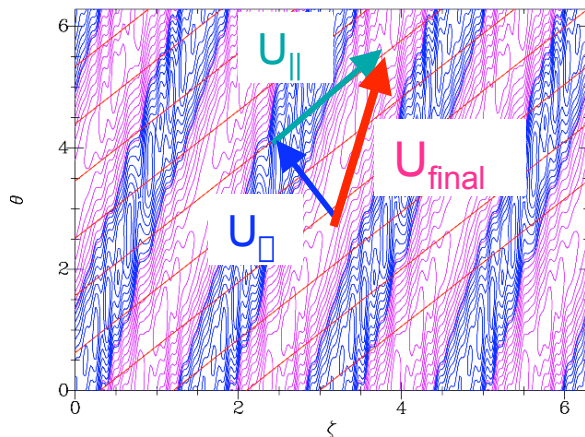
# Compact Stellarator Experiments Optimize Confinement Using Quasi-Symmetry

- Quasi-symmetry: small  $|B|$  variation and low flow damping in the symmetry direction, which allows large flow shear

## Quasi-helical symmetry

$$|B| \sim |B|(m\varphi - n\theta)$$

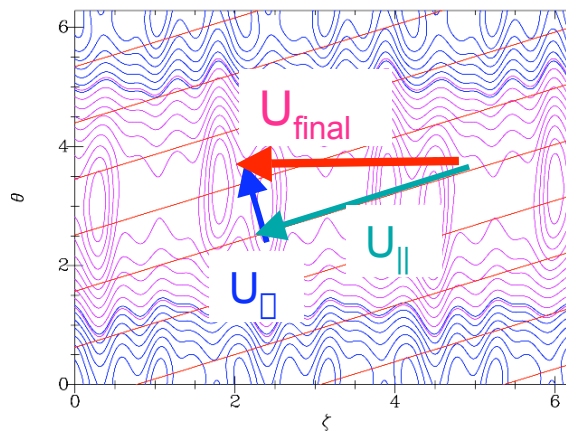
$|B|$  at  $r/a = 0.20$  (blue:  $B < 1T$ , purple:  $B > 1T$ )



## Quasi-toroidal symmetry

$$|B| \sim |B|(\varphi)$$

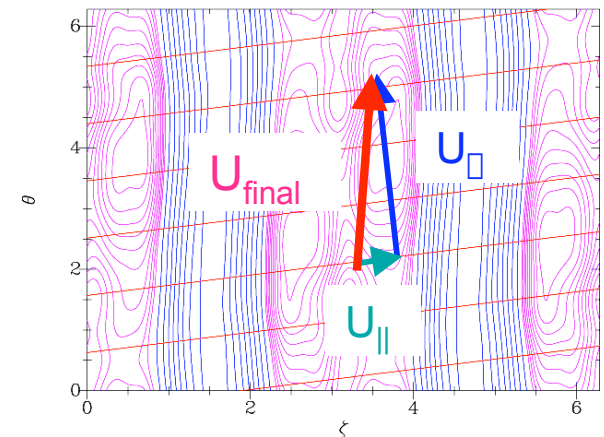
$|B|$  at  $r/a = 0.20$  (blue:  $B < 1T$ , purple:  $B > 1T$ )



## Quasi-poloidal symmetry

$$|B| \sim |B|(\theta)$$

$|B|$  at  $r/a = 0.20$  (blue:  $B < 1T$ , purple:  $B > 1T$ )



- Low effective field ripple for low neoclassical losses
- No/low plasma current for good flux surfaces at both low and high beta

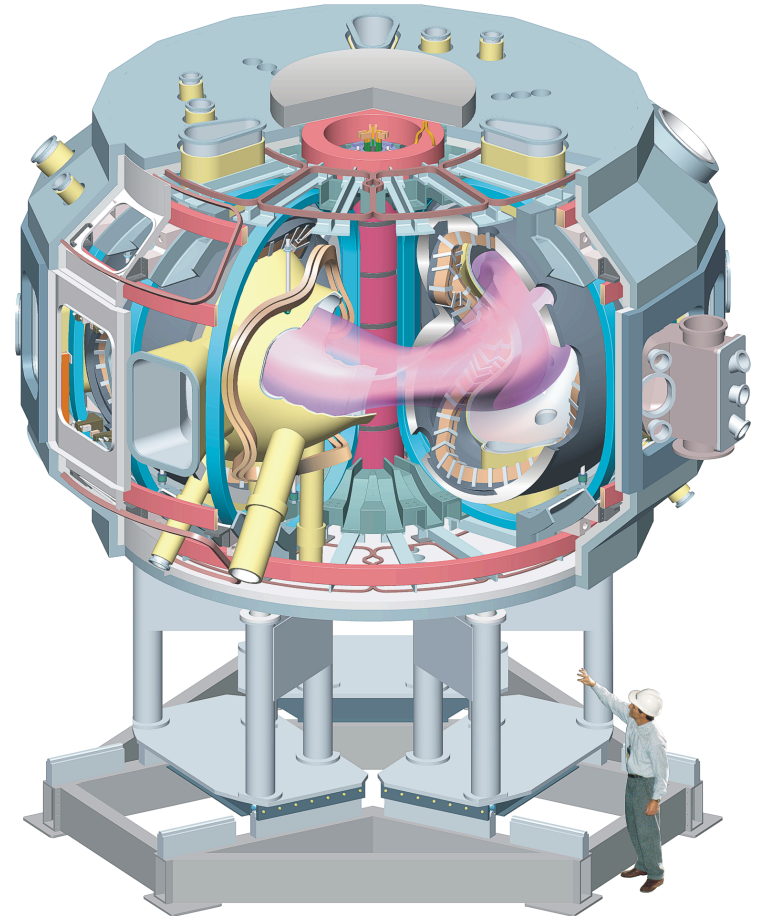
# 3-D Optimized Experiments Designed With Particular Magnetic Configuration Features

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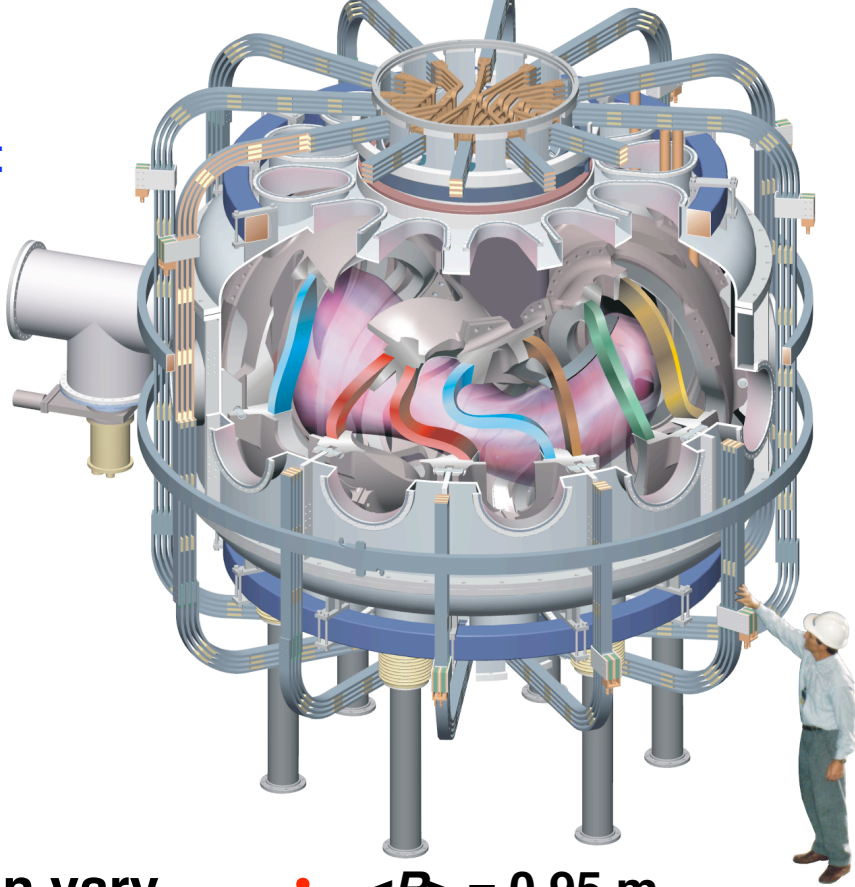
- **NCSX -- stellarator-tokamak hybrid with quasi-axisymmetry**
- **QPS -- stellarator-mirror hybrid with quasi-poloidal symmetry**
- **HSX -- quasi-helical symmetry and low neoclassical transport**
- **CTH -- equilibrium and stability with plasma current at low  $R/a$**

# NCSX Explores Advantages of Quasi-Axisymmetry

- $\langle R \rangle = 1.42$  m,  $\langle a \rangle = 0.33$  m (0.37 m max)  
 $\langle R \rangle / \langle a \rangle = 4.4$ , wide range of configurations
- $B = 2$  T,  $P = 3$ -12 MW
- Operation in 2009
- Objectives: integrated demonstration and understanding of
  - high-beta disruption-free operation with bootstrap current and external transform
  - beta limits and limiting mechanisms in a low- $R/a$  current-carrying stellarator
  - reduction of neoclassical transport by quasi-axisymmetric design
  - confinement scaling and reduction of anomalous transport by flow-shear control
  - islands and stabilization of neoclassical tearing modes by magnetic shear
  - power and particle exhaust compatibility with good core performance



# QPS Explores Quasi-Poloidal Symmetry

- Will study effect of low  $R/a$  and quasi-poloidal symmetry on
    - reduction in neoclassical transport (low effective ripple)
    - reduction in anomalous transport (large poloidal flows,  $E_r$ )
    - equilibrium robustness with strong toroidal/helical coupling
    - healing magnetic islands
    - $\langle \nabla \cdot \mathbf{B} \rangle$  limits and instability character
    - edge divertor topology
  - Extends stellarator database to lowest aspect ratio
  - 9 independent coil current sets; can vary
    - quasi-poloidal symmetry by a factor of 9
    - poloidal flow damping by a factor of 25
    - neoclassical transport by a factor of 20
    - stellarator/tokamak shear
    - trapped particle fraction
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- $\langle R \rangle = 0.95$  m
  - $\langle a \rangle = 0.3\text{-}0.4$  m
  - $\langle R \rangle / \langle a \rangle = 2.7$
  - $B = 1$  T,  $P = 2\text{-}4$  MW
  - $0.15\text{-}T \nabla B$ ,  $I_p = 50$  kA
  - Operation in 2010



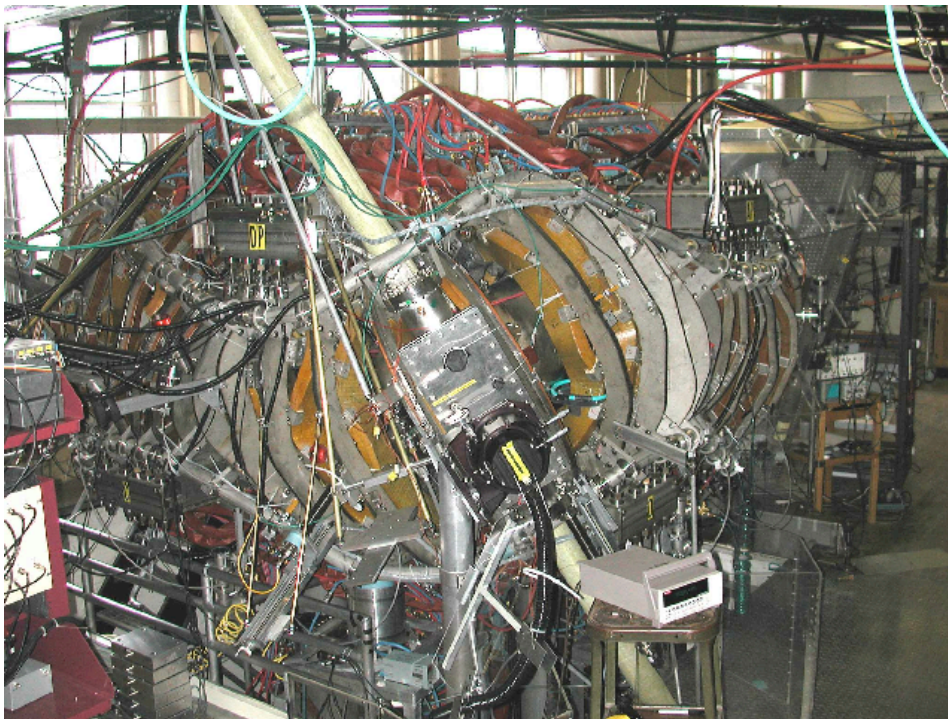
# The HSX Program: World's First Experimental Test of Quasi-symmetry



## Mission: Explore Improvement of Neoclassical Transport in Stellarators

Quasi-helical stellarators have high effective transform,  $\bar{q}_{\text{eff}} \sim 3$  ( $q \sim 1/3$ )

- Reduced particle drift
- Small neoclassical transport
- Low plasma currents; robust magnetic surfaces



- First experimental verification of reduced flow damping with quasi-symmetry
- Confirmation of high effective transform and reduction of direct loss orbits
- Fast particle effects on MHD modes observed due to improved confinement
- Observation of reduced neoclassical thermodiffusion
- Experimental verification of 3-D neutral code DEGAS

$\langle R \rangle = 1.2$  m,  $\langle a \rangle = 0.15$  m,  $B = 1.0$  T, 4 periods, 400-kW 28-GHz ECH

# CTH: Compact Toroidal Hybrid

## Addresses equilibrium & stability in stellarators with current

### Objectives:

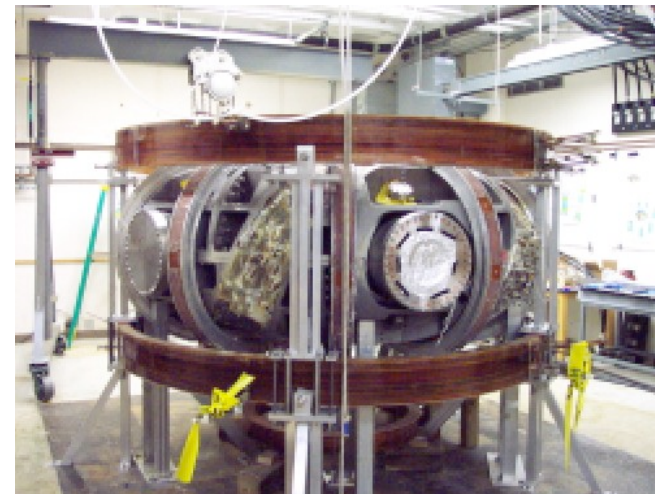
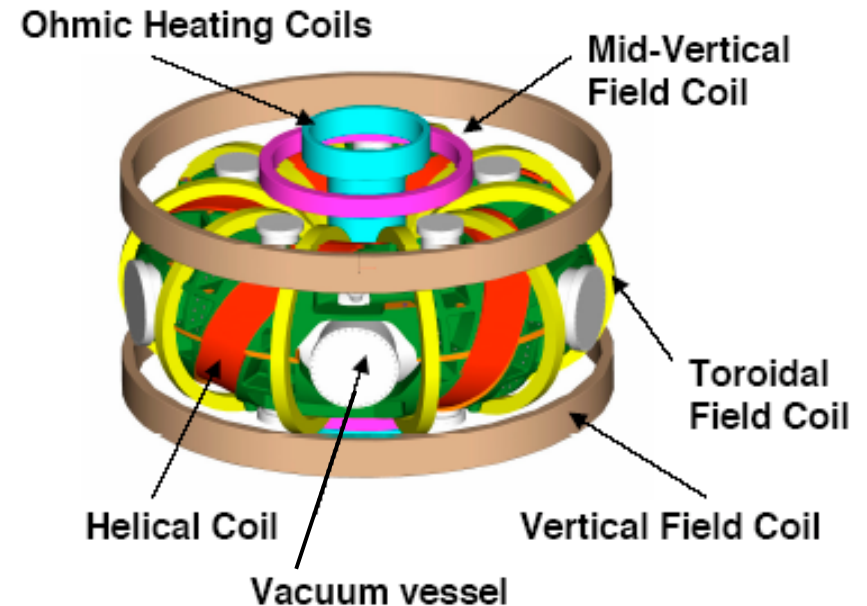
- Reconstruct 3-D plasma equilibrium with V3FIT code & magnetic measurements
- Determine stable operating scenarios and disruption behavior in current-carrying plasmas
- Control static islands in low-aspect ratio helical plasmas

### Addresses key physics areas:

- Physics underlying external stability control
- Understanding current-driven instabilities in stellarators
- Limits of disruption-free operation

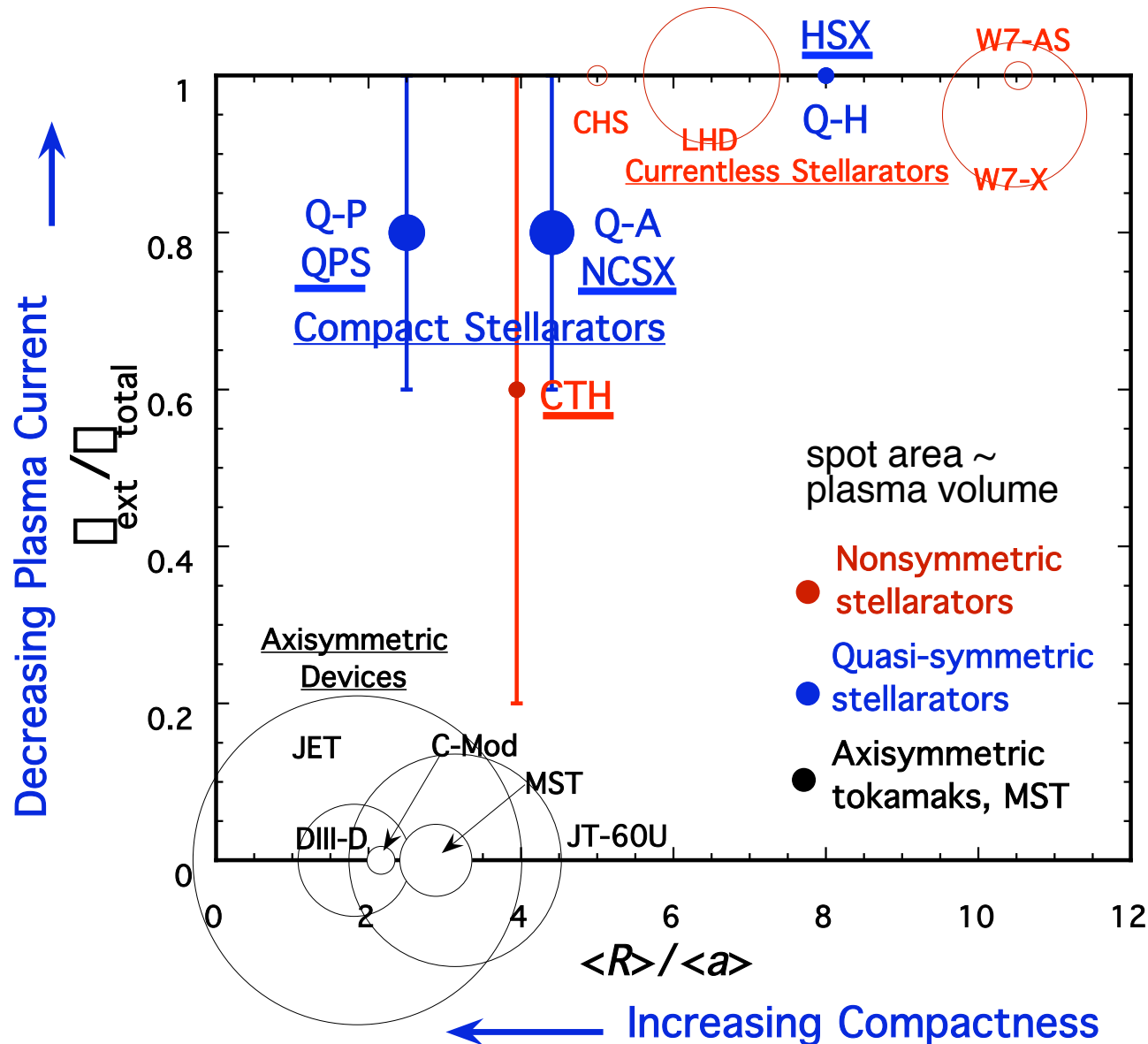
### Parameters:

- $R = 0.75$  m,  $a_{\text{plasma}} \leq 0.18$  m,  $R/a \geq 4$
  - $B = 0.5$  T,  $I_p = 50$  kA, ( $\beta \sim 0.5$ ),  $P \sim 120$  kW
- **First plasma Feb. 22, 2005** (ECH at 0.1T)



CTH in late January, prior to 1st plasma

# Compact Stellarators Bridge between Currentless Stellarators and Lower $R/a$ Tokamaks



# **Compact Stellarator Program Contributes Unique Information on FESAC's High Priority Scientific Questions**

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- 1 How does magnetic field structure impact fusion plasma confinement?**
  - 2 What limits the maximum pressure that can be achieved in laboratory plasmas?**
  - 3 How much external control versus self-organization will a fusion plasma require?**
  - 4 How does turbulence cause heat, particles, and momentum to escape from plasmas?**
  - 5 How are electromagnetic fields and mass flows generated in plasmas?**
  - 9 How to interface with room temperature surroundings?**
- Advantage is wide range of configuration properties**

# 1. How Does Magnetic Field Structure Impact Fusion Plasma Confinement?

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**Understanding the role of plasma shaping on:**

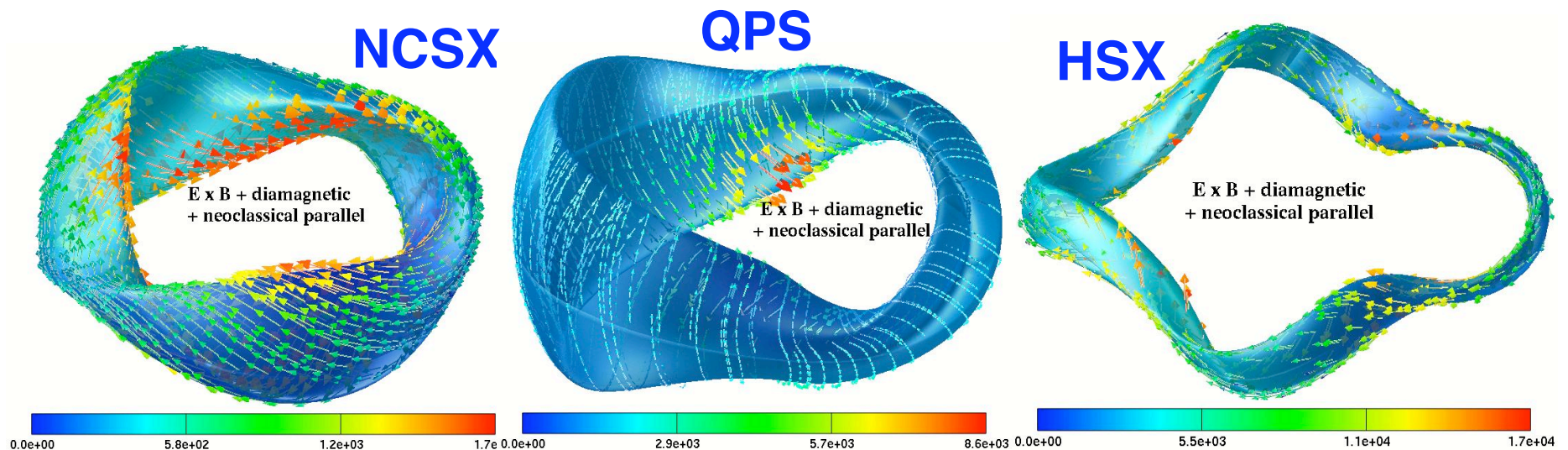
- a plasma confinement**
- b effects of self-generated currents and flows**
- c effects of magnetic structure within the plasma**

**Wide variation of configuration properties is possible in compact stellarators for transport & stability studies**

- **3-D shaping and effective magnetic field ripple**
  - **trapped particle fraction**
  - **amount and sign of shear**
  - **type and degree of quasi-symmetry**
  - **degree of viscous damping and flow shear**
  - **ambipolar electric field and internal transport barriers**
  - **magnetic island size and ergodic regions**
  - **internal vs. external transform**
- + integrated effort in experiment, modeling, and theory**

# Quasi-Symmetry Determines Flow Magnitude and Direction

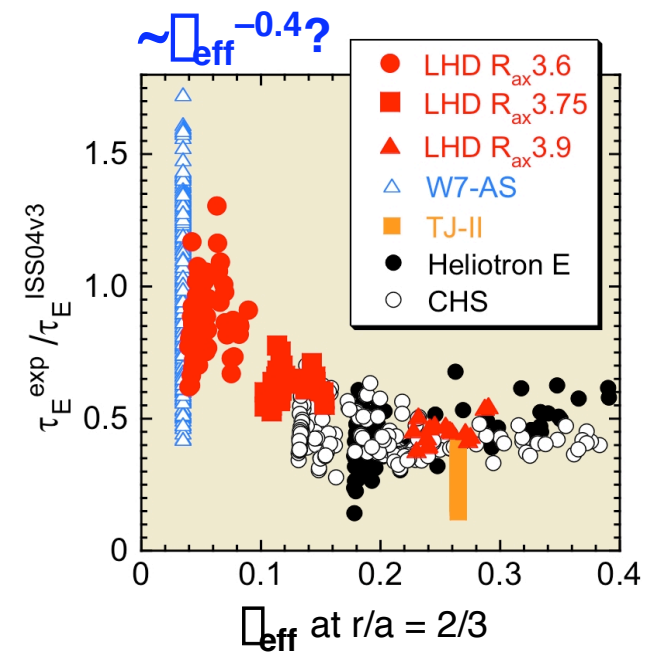
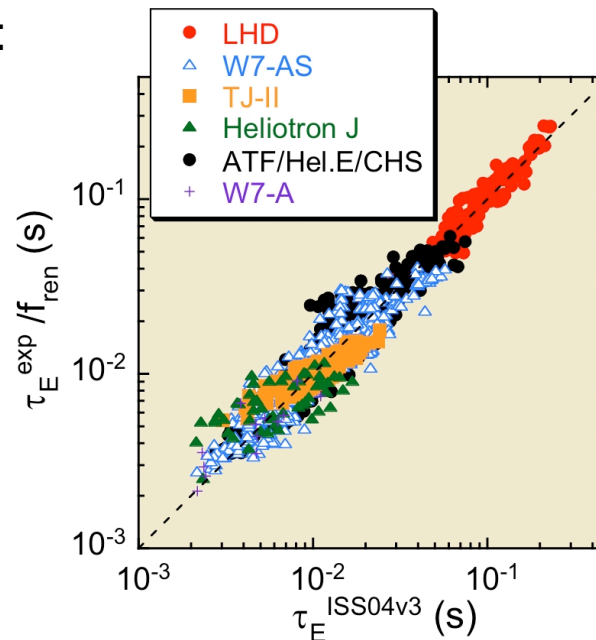
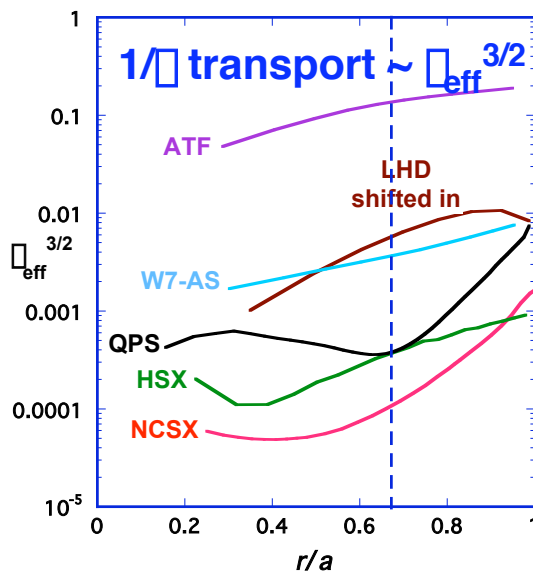
- Low flow damping in symmetry direction allows large flows that can shear apart turbulent eddies and reduce anomalous transport
- Corresponding electric fields and their effect on flows can also affect neoclassical and anomalous transport



□ Can vary damping through external control

# Anomalous Transport May Depend on $\bar{\epsilon}_{\text{eff}}$

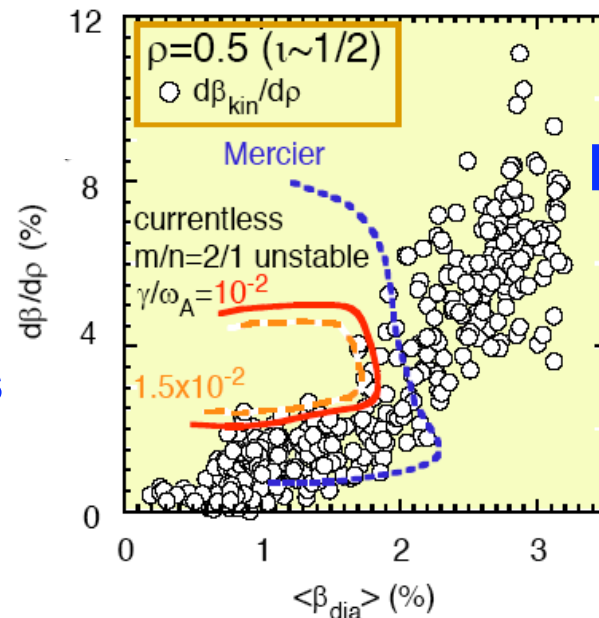
- The large reductions in effective helical ripple  $\bar{\epsilon}_{\text{eff}}$  in compact stellarators is expected to greatly reduce neoclassical transport
- Stellarator database suggests that lower effective ripple may also reduce anomalous transport -- electric field effect?



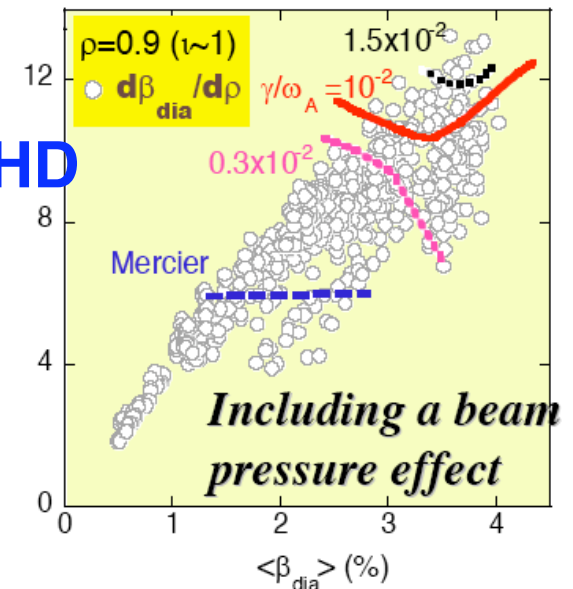
- New research area: scaling of confinement with configuration parameters ( $\bar{\epsilon}_{\text{eff}}$ , aspect ratio, degree of quasi-symmetry, etc.) has not been explored at low aspect ratio or in quasi-symmetric configurations
- Provides insight for other configurations
  - might be tied to flow damping physics
  - $\bar{\epsilon}_{\text{eff}}$  can be varied over a very wide range in a single experiment

## 2. What Limits the Maximum Pressure That Can Be Achieved in Laboratory Plasmas?

- Current data indicates that  $\beta$  in stellarators is not limited by instabilities
  - quiescent plasmas are routinely observed well above linear stability thresholds



LHD

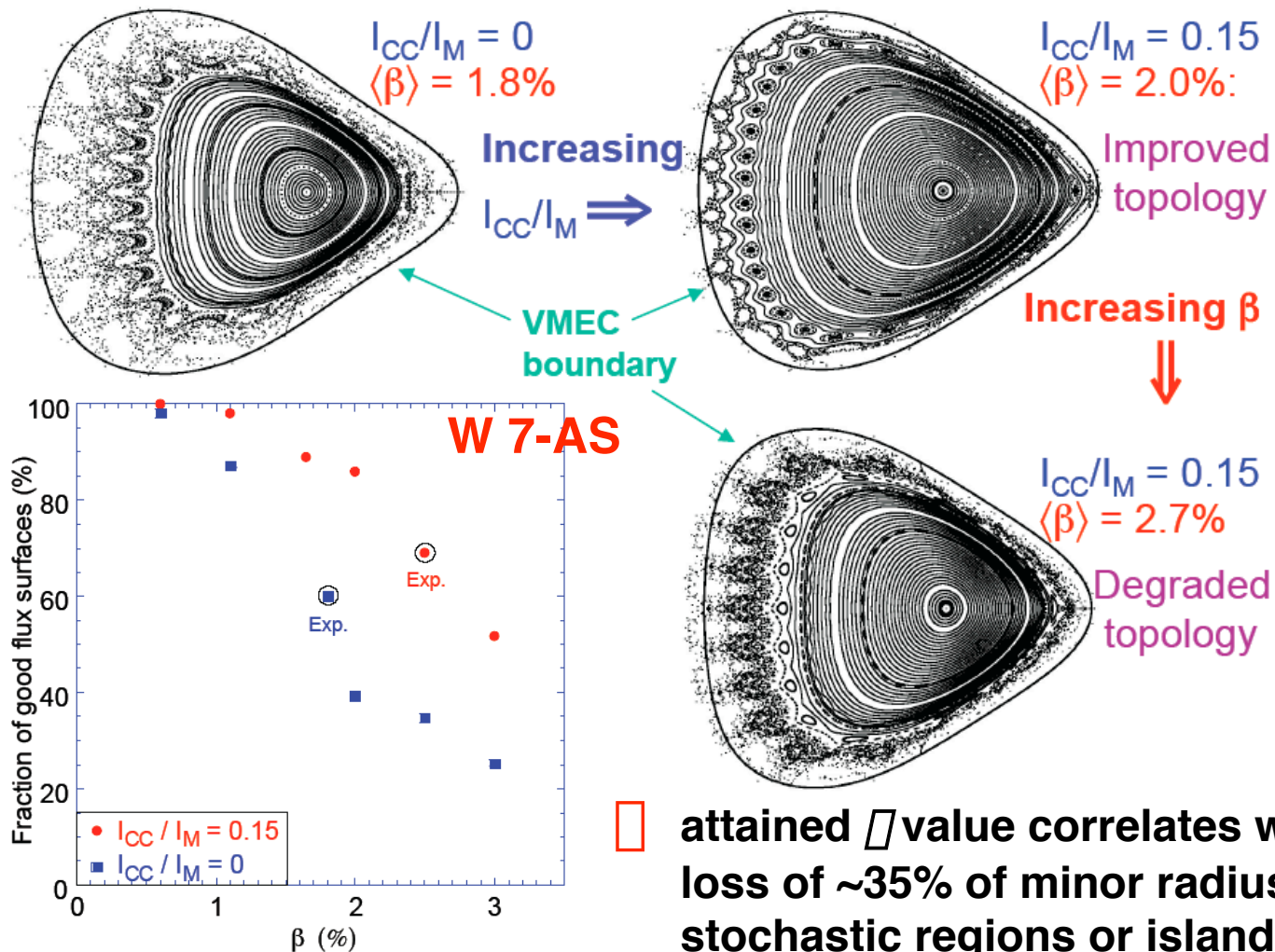


- Character of MHD instabilities is different in stellarators
  - e.g., ballooning instability occurs simultaneously on a surface in tokamaks but occurs progressively line-by-line with different growth rates as  $\beta$  increases in stellarators
- Provides new insight into non-linear character of MHD instabilities

# Observed $\beta$ Limits May Be Due to Equilibrium Limits

Equilibrium is limited by the onset of magnetic stochasticity:

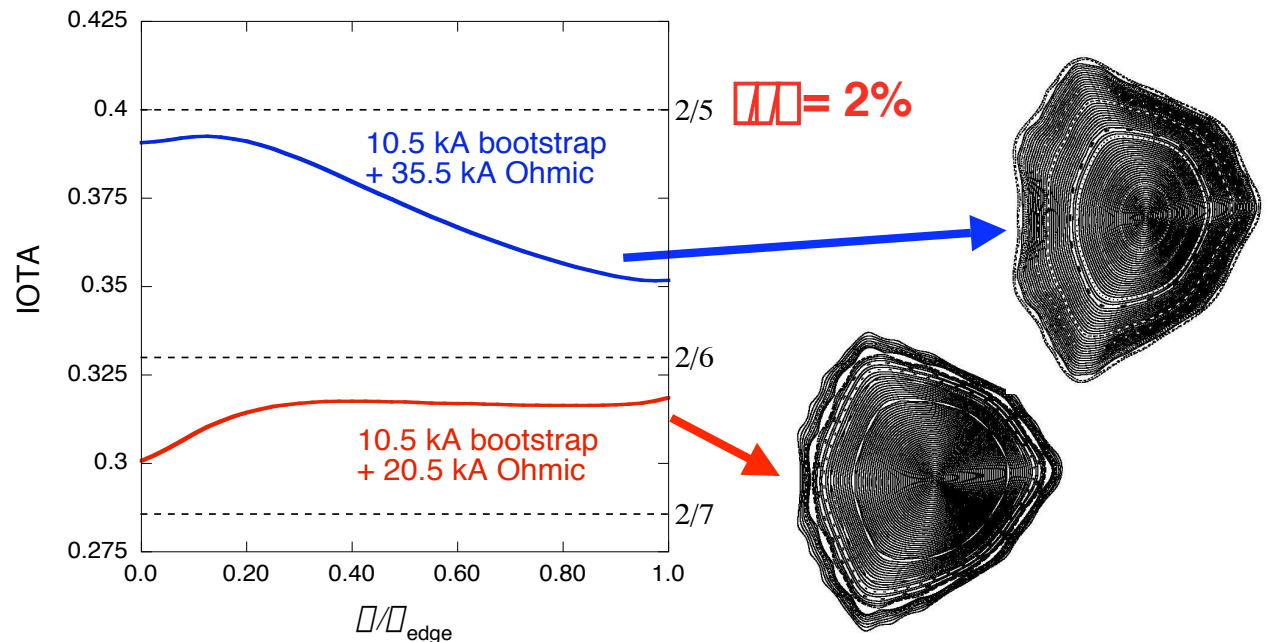
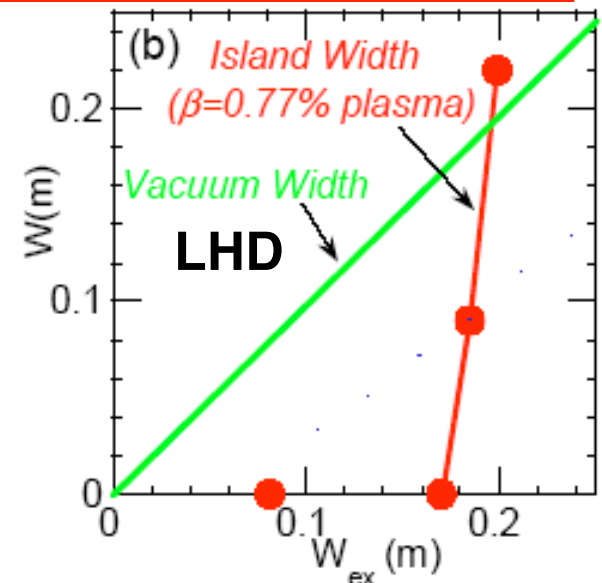
□ Compact stellarators designed to maintain good surfaces at high  $\beta$



□ attained  $\beta$  value correlates with loss of  $\sim 35\%$  of minor radius to stochastic regions or islands

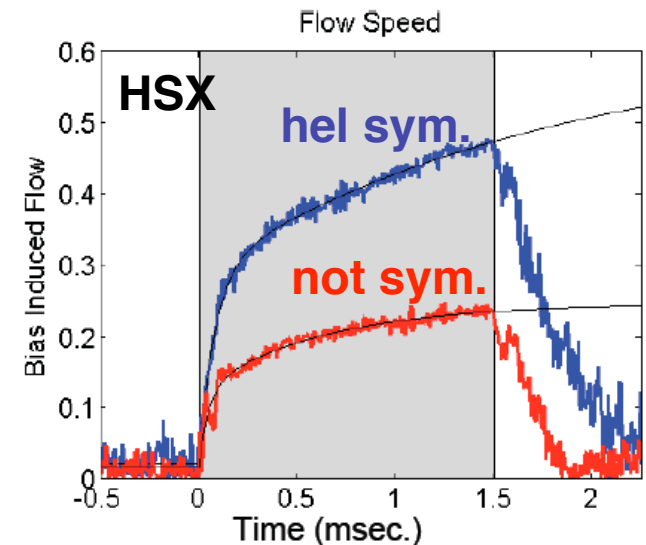
# Magnetic Islands Can Be Controlled

- Compact stellarators are designed to have good flux surfaces
- Self-stabilizing effect of a plasma current (for  $w/a < 0.3$ ), related to tearing modes in tokamaks
- Bootstrap and Ohmic current tailoring of the  $q$  profile to avoid low-order resonances
- Can control with external coils



### 3. How Much External Control Versus Self-organization Will a Fusion Plasma Require?

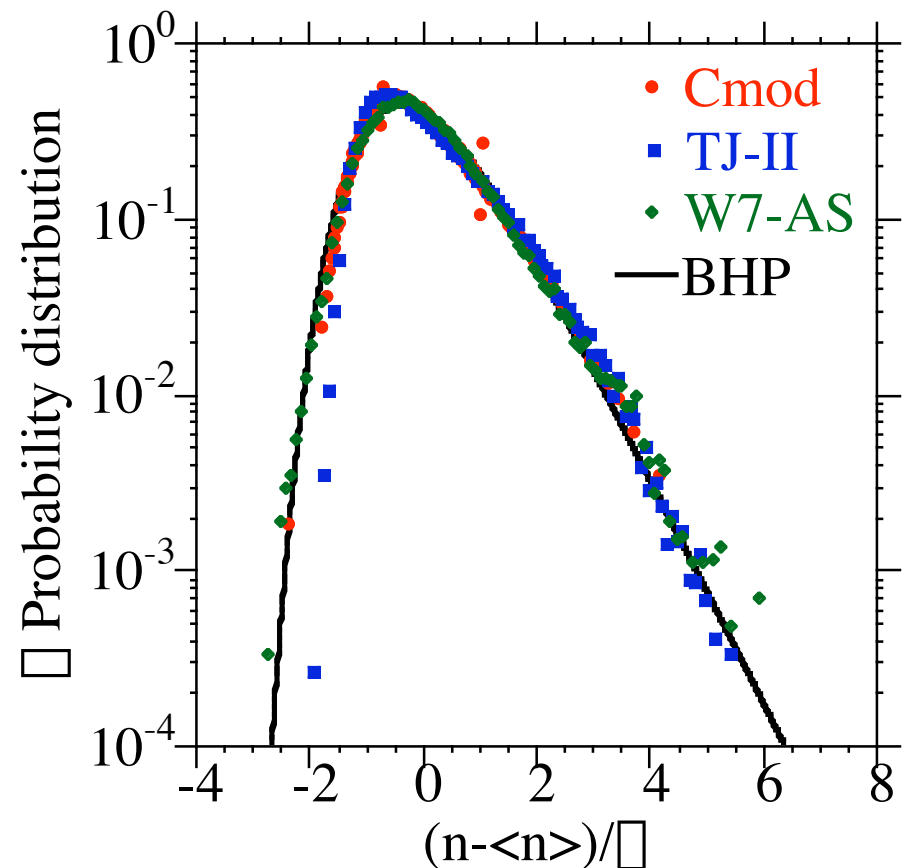
- a Understanding the use of dominant external control (e.g. externally generated confining magnetic fields or flows)
- b Understanding and controlling pressure-gradient-driven plasma currents and flow self organization



- W 7-AS shows that externally controlled plasmas allow quiescent, long-lasting, non-disruptive plasmas at high beta, even without compact stellarator optimization
- LHD shows that can control electron-root to ion-root transition and internal transport barriers
- The field can be tailored to control current-driven and pressure-driven instabilities
- External control reduces self-organization and nonlinearity in equilibrium and stability, avoids kink instabilities

## 4. How Does Turbulence Cause Heat, Particles & Momentum to Escape From Plasmas?

- The functional form of the normalized probability distribution of edge fluctuations in different toroidal devices is very similar
- This behavior is seen in other systems close to a critical point, implying correlations
- Does the behavior of the edge layer in toroidal plasmas belong to this universal class?
- Does it differ for quasi-symmetric compact stellarators?
- What is the physics behind this?



# Differences in Magnetic Structure Influence Core Turbulence and Confinement

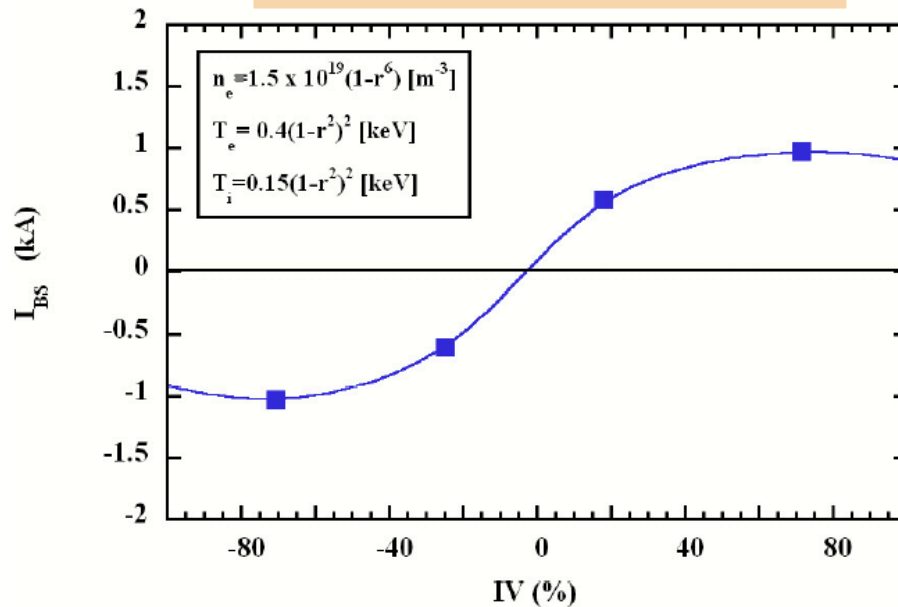
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- Low flow damping with quasi-symmetry allows zonal flow stabilization
- Reversed magnetic shear can stabilize trapped particle instabilities, increase damping of ITG modes
- Internal islands can produce  $E \times B$  shearing, generating transport barriers

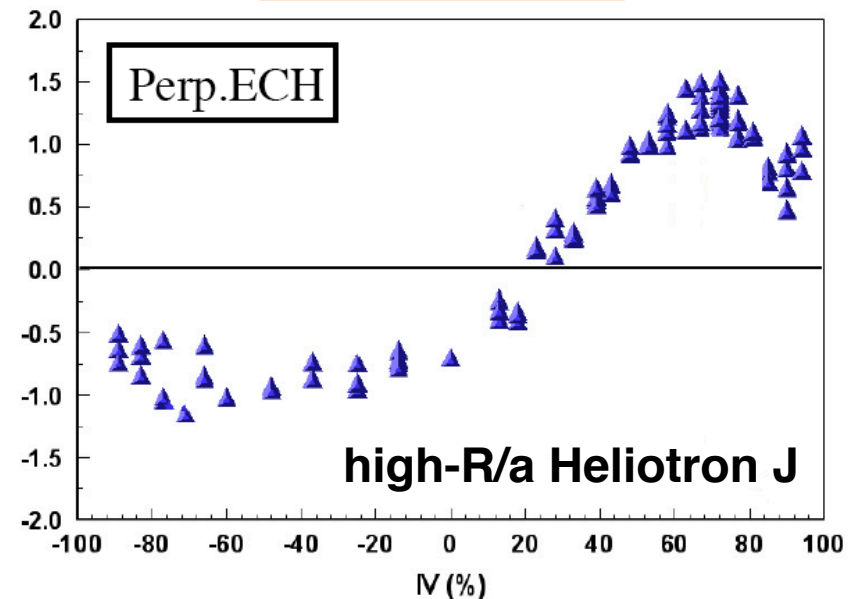
## 5. How Are Electromagnetic Fields and Mass Flows Generated in Plasmas?

- **Examples:  $E \times B$  flows (discussed earlier), control/reversal of bootstrap currents**

MODEL CALCULATION



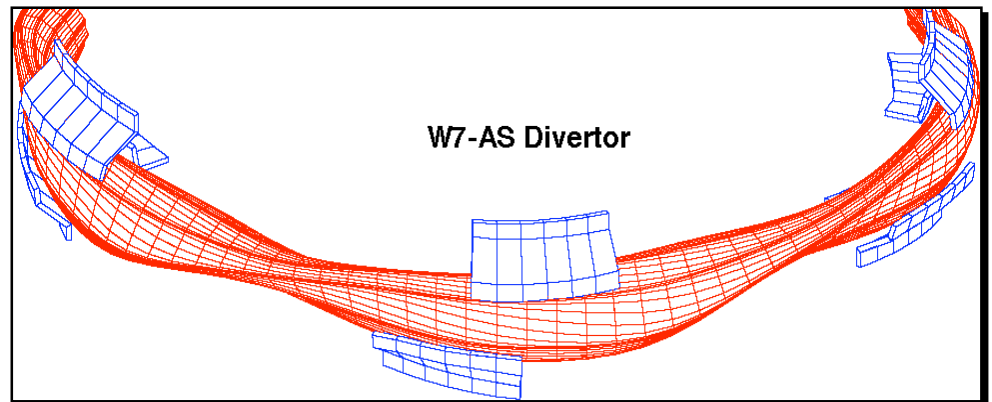
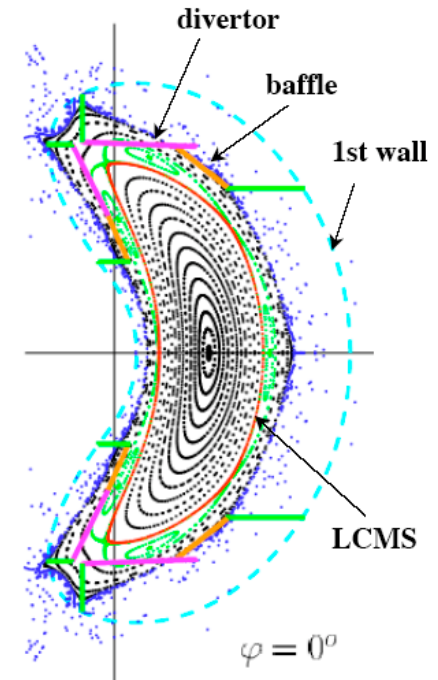
EXPERIMENT



- **The type of quasi-symmetry and low aspect ratio affect the magnitude of the bootstrap current**

## 9. How to Interface to Room Temperature Surroundings?

- 3-D shaping flexibility allows different edge strategies:
  - diverted field lines, island divertors, ergodic edges, or combinations
- W 7-AS and LHD divertors have successfully demonstrated density and impurity control, including high- $\beta$  plasmas
  - need to demonstrate in compact stellarators
- Good or enhanced confinement obtained at very high density in stellarators
  - combined with lack of need for current drive allows low temperature edge plasma, easing divertor design



# 3-D Geometry and Low Aspect Ratio Drive Theory Development

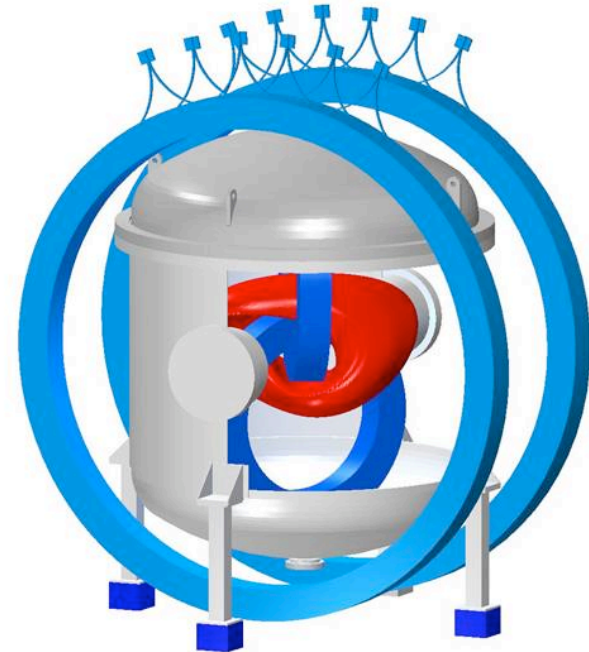
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- **Plasma equilibrium**
  - toroidal and poloidal variation are strongly coupled -- need to improve representation, convergence more demanding
  - need to improve modeling of plasma response
- **MHD stability**
  - need to understand observed nonlinear mode saturation
  - interpretation of high-n ballooning stability differs because calculations don't apply to entire surface as in a tokamak
- **Transport**
  - need nonlinear simulations of expected turbulent transport
  - need to include magnetic islands and 2-D variations within a flux surface

# Compact Stellarators Impact Other Areas

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- **Confinement of non-neutral and  $e^+/e^-$  plasmas (Columbia Non-Neutral Torus)**
  - simple coils and low-R/a plasma designed with tools developed in compact stellarator program
- **3-D nature of space plasmas**
  - uses theoretical methods for treating magnetic problems (solar flares, galaxy structure)



# HSX Budgets and Milestones

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- **FY 2006 -- \$1,475k**
  - full 200 kW operation and magnetic field of 1 T
- **FY 2007 -- \$1,475k** (reduce staff by 1.5 to maintain grad. students)
  - increase ECH power to 400 kW
  - measure thermal conductivity by heat pulse propagation
  - initial electric field measurements
  - eliminate loading test for HHFW at low power
- **10% decrement in FY 2007 -- \$1,328k**
  - delay electric field and core turbulence measurements
  - another 1 FTE reduction in staff
- **Full-use budget in FY 07 -- \$1,949k** (supported by 2004 review)
  - clear demonstration of differences in neoclassical transport with electric field
  - ICRF program, ion heating, higher density operation, more flexibility, NCSX support
  - core turbulence studies

# CTH Budgets and Milestones

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- **FY 2006 -- \$450K**
  - tests of V3FIT with data from external magnetic diagnostics
  - initial stability and disruption characterization w/SX arrays
- **FY 2007 -- \$450K (delay/defer post-doc hire; maintain 3 grad. stud.)**
  - implement advanced 3-D reconstruction with internal B measurement from polarimeter/interferometer
- **10% decrement -- \$405K (eliminate post-doc & 1 grad. student)**
  - delay quantitative MHD instability and disruption studies
  - delay polarimetry results
  - eliminate plans for ICRF for flexible range of operation
- **10% increment -- \$500K in FY 2007**
  - restore a grad. student
  - restore implementation of ICRF heating system & utilization of polarimetry

# QPS Budgets and Milestones

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- **FY 2006 -- \$920k (vs \$1433k in FY 2005), ORNL + PPPL**
  - finish machining modular coil winding form
  - wind full-size R&D modular coil with cable conductor
- **FY 2007 -- \$920k, ORNL + PPPL**
  - complete vacuum canning and potting the R&D coil
  - test full-size R&D modular coil & measure current center
- **10% decrement -- \$828k, ORNL + PPPL**
  - delay R&D coil tests and current center measurements to FY 08
  - reduce Univ. Tenn. support
- **Full use budget -- \$5.1 M (from CD-1 approval documentation)**
  - complete prerequisites for CD-2 milestone
  - complete Final Design Reviews for modular coil winding forms and vacuum vessel
  - complete prerequisites for CD-3 milestone for procurement and fabrication of components
  - complete design needed for production contract for vacuum vessel

# SUMMARY

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- The components of the integrated national compact stellarator program are designed and coordinated to address important US program issues (FESAC)
- Unique features: quasi-symmetry, good flux surface with configuration flexibility, and compactness
  - to advance toroidal confinement understanding
  - for concept improvement
- Complements larger tokamak and international stellarator programs and aims at an improved reactor vision